DSN Water Vapor Radiometer Development—Recent Work, 1978

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A water vapor radiometer (WVR) has been developed that measures the atmospheric noise temperature at two different frequencies near 22 GHz. These noise temperatures are used in empirical-theoretical equations that yield tropospheric range delay, in centimeters, through the atmosphere along the beam of the WVR. This range correction is then applied, as needed, to measurements concerning spacecraft range and to VLBI baseline determinations. This report discusses the WVR design and calibration techniques.

I. Introduction

Development work has continued on the water vapor radiometer (WVR). This article will discuss progress since the last reports (Refs. 1 and 2). Also mentioned are new frequencies that resulted from analytical support activities and a discussion of the calibration load techniques that have evolved since this work started. The cold calibration load mentioned in Refs. 1 and 2 has been replaced by a hot load. The block diagram of the instrument is unchanged since Ref. 1 except for this change in load design. Figure 1 shows the WVR in its current configuration.

A formal set of technical specifications and recommendations for WVRs has been generated (Ref. 3), with inputs from the outside scientific community.

II. Calibration Loads and Techniques

In the water vapor radiometer, the radiometric noise temperatures of the sky at two frequencies near the water vapor resonance line, 22.235 GHz, are used to infer the phase delay through the atmosphere. To get an accurate measurement of these noise temperatures, the radiometer can be accurately calibrated by using waveguide calibration loads whose absolute radiometric temperature has been determined from insertion loss and physical temperature measurements (Ref. 4).

The method of using absolutely calibrated waveguide loads to calibrate a radiometer depends on several assumptions:

(1) The Rayleigh-Jeans approximation to the Planck blackbody-radiation law must hold at the frequency of interest.

(2) Thermal gradients between the physical temperature sensor and the passive microwave load radiating region are negligible.

(3) Energy radiated by the load is not significantly reflected in reaching the radiometer receiver.

(4) Insertion losses and their physical temperatures between the load and the radiometer receiver are known.

(5) The temperature sensor that measures the physical load temperature must be of sufficient accuracy (Ref. 5).

It is the aggregate effect of all these uncertainties (Ref. 6 identifies ten of them) that leads to the total cal-load temperature error. It should be noted that an ambient temperature cal-load can be designed to have no significant temperature gradients. In this case, the radiometric temperature of the ambient load is equal to its physical temperature (the load looks like a perfect blackbody):

$$T_{AR} = T_{AP} \tag{1}$$

where for future reference,

T is temperature in kelvins

A is ambient

R is radiometric

P is physical

The best radiometer measurements are achieved when the instrument calibration curve extends on either side of the desired measurement region, i.e., data can be interpolated rather than extrapolated. In the case of the WVR, measured sky temperatures are as low as 10 K; it is impractical to try to achieve the true interpolation condition for the calibration curve. However, having one calibration reference load near the coldest expected values would still be desirable to minimize the strong "leverage" effects that often result when using an extrapolated calibration curve.

To achieve these desired colder temperatures, several refrigeration devices were tried. The first was a two-stage Peltier junction, which was quite reliable but achieved only -40°C (233 K), and then only with a two-gallon-per-minute total-loss, water-cooled heat sink. The second device was a reciprocating air-expansion refrigerator that achieved -90°C (183 K), but required, along with its air source, high maintenance.

The third cooling device was a multistage, closed-cycle fluorocarbon refrigerator that achieved -120°C (153 K) and showed great promise. The fundamental problem with this machine was that it was intended for a laboratory environment, and after several field tests it failed. The manufacturer did major redesign and modification for field use, but before it could be tried again, the decision was made to abandon the cooled cal-load and proceed with the development of a heated reference load. This decision was based on a critical examination of the complexity and potential unreliability of available cryogenic refrigerators when used under field conditions.

If the hot cal-load were to be absolutely calibrated, all of the previously mentioned uncertainties in its noise output would be multiplied by the leverage effect of having both cal-loads far removed from the sky temperature. For example, if the two cal-loads and sky are 400 K, 300 K, and 20 K, respectively, cal-load uncertainties are multiplied by a leverage of 2 to 3 for antenna temperature determinations in the region of 0 to 100 K. Figure 2 illustrates this condition. However, this leverage degradation could be overcome if the cal-load could be calibrated using the cosmic background temperature of 2.7 K as a calibration source via a technique known as "tipping curves." This technique does not require accurate knowledge of insertion losses between the load and receiver.

A tipping curve is done by pointing the radiometer antenna at elevation angles nominally corresponding to one, two, three, and four air masses (elevation angles of 90, 30, 19.47, and 14.47 deg respectively) and noting the radiometer output in "counts." This information is used to extrapolate to the value of counts at zero air masses. Since this condition of zero air masses corresponds to viewing only the cosmic background radiation of 2.7 K, the number of counts at 2.7 K can be derived. The relationship between counts at zero, one, and two air masses is, as an example (to a good approximation), $N_0 = 2N_1 - N_2 = N_c$, the counts corresponding to the cosmic background radiometric noise temperature of 2.7 K (T_c). The radiometer is then switched to the ambient cal-load and the counts N_A are noted. From these measurements, the radiometer gain in counts/kelvin is found to be

$$K_1 = \frac{N_A - N_C}{T_{AP} - T_C} \tag{2}$$

Sky noise temperature can then be determined from

$$T_S = T_{AP} - \frac{1}{K_1}(N_A - N_S) \tag{3}$$

where N_S is the counts when the radiometer views the sky.

It should be noted that these equations ignore several small correction terms to avoid complicating the discussion. In actual practice, various corrections related to noise temperature saturation and instrument parameters are applied. The sky temperature can be determined as shown above since the system has been designed to be linear. A good feature of this tipping curve calibration is that the cosmic background radiation, used as an equivalent cold calibration load, is actually lower than the sky temperatures the instrument normally measures. When used in conjunction with the ambient load, as is done here, the resulting calibration curve allows sky measurements to be interpolated rather than extrapolated. This means that sky measurement errors, due to cal-load uncertainties, are less than these cal-load uncertainties themselves.

There are some drawbacks to this method. First, the atmosphere is not always well-behaved enough to allow tipping curve calibrations of instrument gain. The possibility of some "lumpiness" in water content will prevent a correct extrapolation of the tipping curve data to zero air masses. To assist in dealing with this problem, a four elevation point tipping curve is used to verify proper atmosphere stratification (atmospheric parameters constant with respect to horizontal movement). The second drawback of this method is that accomplishing a good tipping curve calibration is relatively time-consuming.

Since the radiometer may not hold its gain calibration for the long periods of time between tipping curve tests, a second calibration method is carried out by using the ambient load in conjunction with some nonambient load. In the case of the present WVR, high reliability could not be achieved with coolers for a cold cal-load, and it was decided to use a hot cal-load as the nonambient load.

It is possible to solve for the radiometric noise temperature of the hot load by using the tipping curve derived gain for the radiometer and switching to the hot cal-load as an additional real-time step in the tipping curve sequence. Then the hot load radiometric noise temperature can be calibrated with relationship

$$T_{HR} = \frac{1}{K_1} (N_H - N_A) + T_{AP} \tag{4}$$

In actual practice, the radiometric hot load temperature will be somewhat less than (but strictly related to) its physical temperature. Since the stability of the hot cal-load, a passive device, is many times better than that of the radiometer, an active device with over 100 dB system gain, the calibrated hot load can be used in radiometer measurements between infrequent tipping curve calibrations.

This is done by defining a new gain based on the now-calibrated hot load,

$$K_2 \equiv \frac{N_{H2} - N_{A2}}{T_{HR} - T_{AP2}} \tag{5}$$

where the subscript 2 refers to the latest real-time determination of counts and radiometric temperatures.

Ideally, in a drift-free instrument, $K_1 \equiv K_2$. In operation, the instrument measures counts on sky, hot load, and ambient load, and physical temperatures on hot load and ambient load. Equation (5) is evaluated each time a sky temperature measurement is made. The resulting new K_2 (determined every 5 minutes, or so) is used in real time to determine radiometric sky temperatures:

$$T_S = T_{AP2} - \frac{1}{K_2} (N_{A2} - N_S) \tag{6}$$

The value of K_2 can be continuously compared to K_1 (the tipping curve derived gain) and its previous values as a monitor of radiometer performance.

III. Frequency Selection

The WVR frequency pair of 18.55 and 22.235 GHz were originally chosen only on the basis of sensitivity to separation of the noise temperature effects of water vapor from water droplets (clouds). Frequencies near the resonance line (designated probing frequencies) are more sensitive to vapor than frequencies well off resonance (designated reference frequencies).

Possible pairs were 26.5/22.2, 18.0/22.2, and 31.4/22.2 GHz, for reference and probing frequencies respectively, in the order of increasing accuracy to perform the measurement. Since the 18.0/22.2-GHz frequency pair would achieve almost the same accuracy as the 31.4/22.2-GHz pair, and could be accomplished in a single waveguide-band system, it was chosen for this radiometer.

More recent advanced models have shown that the relationship between noise temperature and phase delay, both induced by atmospheric water vapor, is excessively altitude-profile dependent with the 18.0/22.2-GHz frequency pair. This causes an additional tropospheric delay error source due to modeling error. However, several other frequency pairs exhibit much lower vapor profile dependency (Ref. 7). The two best frequency pairs are 20.0/26.5 GHz and 20.3/31.4 GHz. Analysis predicts that both of these pairs will have an error in measuring water vapor induced phase delay of less than 2 cm rms down to 15 deg elevation (~4 air masses) under nonprecipitating weather conditions. The relative accuracy of the two pairs favors the 20.3/31.4 pair slightly, about 15 percent (1.5 mm) at zenith, decreasing to equality at 15 deg elevation.

Since the performance figures mentioned are based on an analytical model, it would seem prudent to experimentally verify them. A NEMS (Nimbus E Microwave Spectrometer) has been refurbished and retuned to 21.0/31.4 GHz. (This radiometer would not operate at a frequency less than 21.0 GHz without serious performance degradation.) NEMS will be used to verify the 20.3/31.4-GHz pair. This modification is now complete and tests are awaiting completion of software development for the radiometer microcontroller.

To verify the one-band frequency pair, 20.0/26.5 GHz, it was proposed to modify the DSN Developmental WVR presently at 18.55/22.235 GHz. This modification consists of changing the local oscillators, mixer, isolators, and horn antenna. The work has been completed except for the antenna. Since there exists a large amount of operational history with this WVR at the 18.55/22.235-GHz frequency pair, the option of restoring this frequency capability has been included in the modification package. The installation of the modification kit that changes between the 18.55/22.235-GHz pair and the 20.0/26.5-GHz pair requires about one day. In fact, this option has been exercised once already in support of a VLBI experiment scheduled at DSS 13 during August 1978.

One observation regarding the relative desirability of the 20.3/31.4- and 20.0/26.5-GHz pair is offered here. A 20.3/31.4-GHz WVR requires two complete and independent microwave receivers, their associated antennas and calibration loads, while a 20.0/26.5-GHz WVR requires only a single microwave receiver and associated parts. A life-cycle cost analysis (Ref. 8) shows a 25 to 30 percent advantage in favor of the 20.0/26.5-GHz pair when examining the microwave portion of the WVR system only, simply due to fewer components, and only a small decrease in performance (~1.5 mm rms additional delay error). These accuracy figures are modeled and have not yet been experimentally verified.

IV. WVR Calibration and Field Tests

During August and December 1977, a series of WVR antenna temperature measurements were made at Edwards Air Force Base, about 50 miles north of Los Angeles in the Mojave Desert. Radiosondes are launched daily there; and simultaneous WVR microwave measurements were made. Radiosondes measure temperature, pressure, and relative humidity in flight and these can be used to determine the tropospheric range delay effect of the atmosphere along the path of the radiosonde.

Comparison of microwave and atmospheric measurements results in a WVR calibration linking antenna noise temperature and tropospheric delay. Tipping curves were also carried out to determine the radiometric temperature of the hot calibration load.

Data from the Edwards tests are still being examined. Preliminary studies indicate that the experimental measurements encompass primarily clear atmospheres, with water vapor only and no liquid water (clouds) present. This cannot be considered a sufficient data base from which to calibrate the WVR completely; however, certain theoretical considerations may be invoked to generalize the WVR calibration. A complete calibration analysis and description of VLBI support tests will appear in a later volume.

V. Future Work

The DSN Developmental WVR will be used in conjunction with Project ARIES (Astronomical Radio Interferometric Earth Surveying) (Ref. 9). Additional work should be done to experimentally verify the analytical model used in selecting optimum frequencies. This could be done by completing the frequency modifications to both the NEMS radiometer and DSN Developmental WVR, followed by their use in VLBI measurements and direct comparison with a LASER/microwave ranging instrument (Ref. 10). Additional radiosonde/WVR comparisons should be made to calibrate the WVR over a wide range of atmospheric conditions.

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Appendix

The hot cal-load used in the DSN water vapor radiometer is a JPL-fabricated waveguide unit. The waveguide housing is a 5.08-cm-diameter × 14-cm-long copper bar, into which a WR42 waveguide size hole is machined. The load element is a 10.2-cm-long, compound single-taper piece comprised of 60 percent beryllium oxide homogeneously mixed with 40 percent silicon carbide. This material mixture combines good thermal conductivity (2.2 W/cm °C compared with 3.9 W/cm °C for the copper housing) and excellent microwave qualities (36 dB/cm loss). Reflection coefficient of the completed load over the frequencies of interest is better than 0.008. The heater is wound on the copper housing insulated by a 0.08-mm mica sheet. This is then surrounded by a 4-cm layer of molded ceramic fiber insulation and assembled into a cylindrical aluminum housing to provide mechanical support and mounting capability. Heat leakage from the assembly is 40 W at 0°C ambient and 150°C load temperature, well within the heating capability of 100 W. A photograph of the microwave components of this load is shown in Fig. 3. This load was installed in June 1977, and has been used for all tests since then.

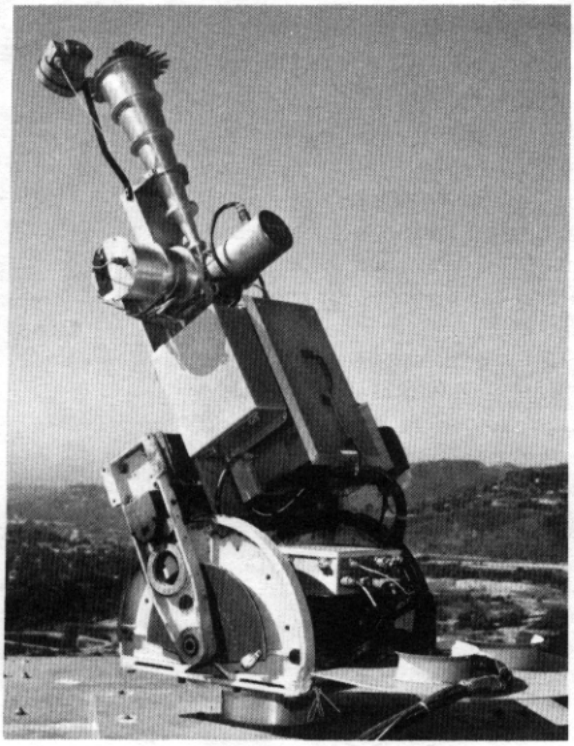

Fig. 1. Water Vapor Radiometer

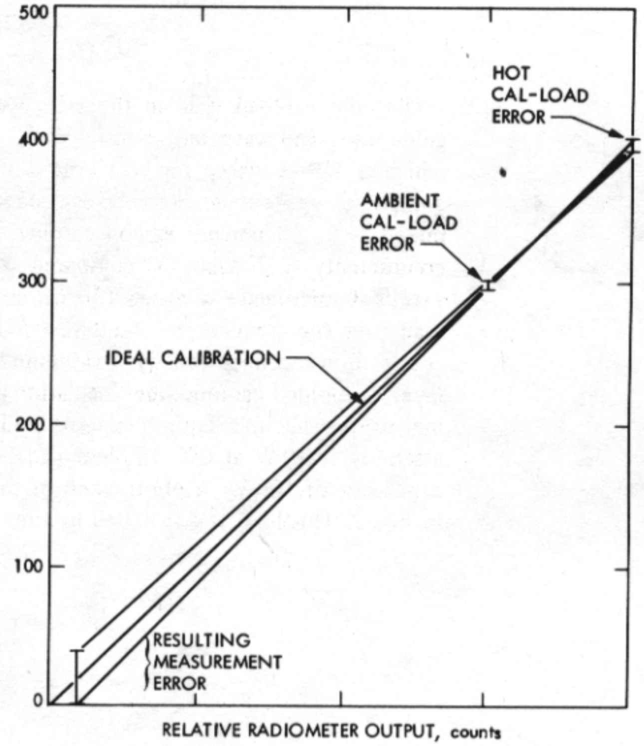

Fig. 2. Effect of calibration load error on antenna temperature determination

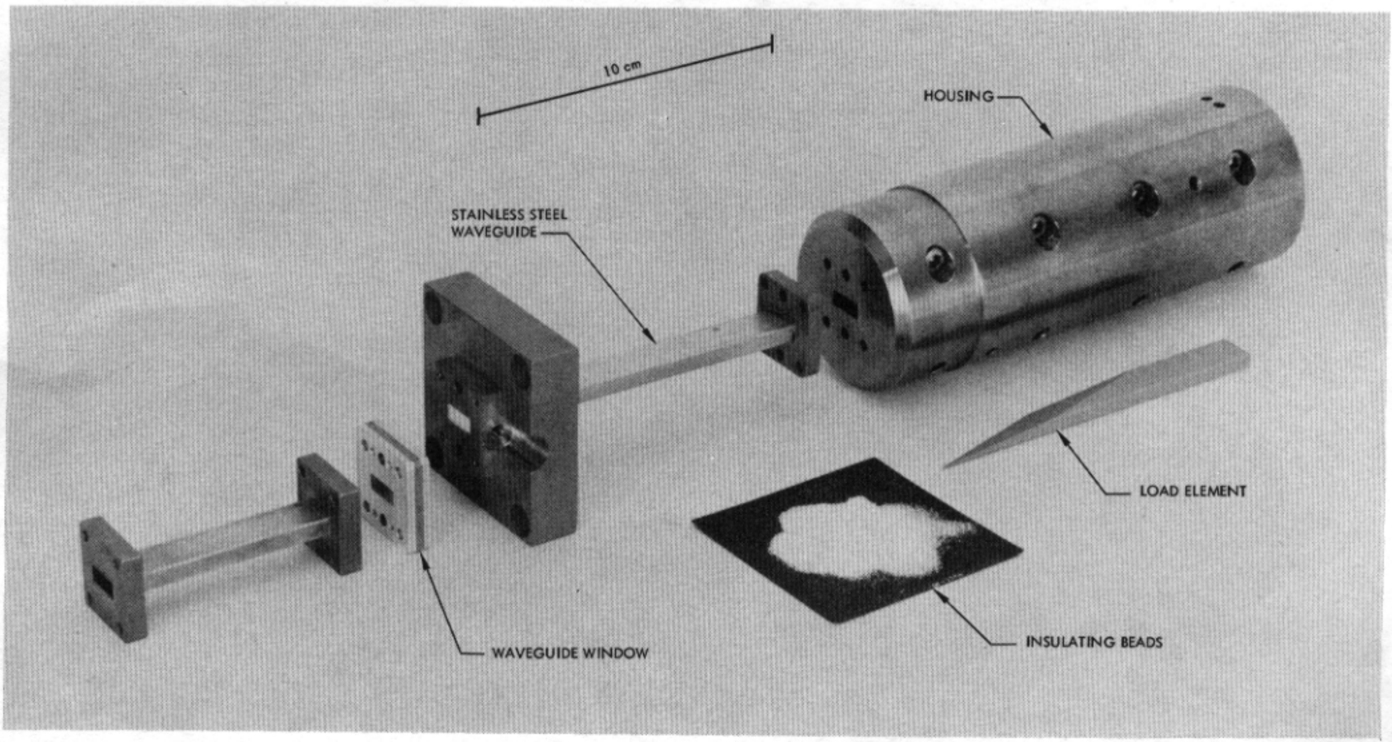

Fig. 3. Exploded view of microwave components of hot calibration load